

This is the published version of a paper published in *Experimental Thermal and Fluid Science*.

Citation for the original published paper (version of record):

Morteza, G., Nader, N. (2015) Thermal performance of screen mesh heat pipe with Al₂O₃ nanofluid. *Experimental Thermal and Fluid Science*, 66: 213-220

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-166178

Experimental Thermal and Fluid Science 66 (2015) 213-220

Contents lists available at ScienceDirect



Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs



Thermal performance of screen mesh heat pipe with Al₂O₃ nanofluid



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ARTICLE INFO

Article history: Received 10 October 2014 Received in revised form 17 February 2015 Accepted 29 March 2015 Available online 6 April 2015

Keywords: Heat pipe Nanofluid Thermal resistance Screen mesh Two-phase heat transfer

ABSTRACT

This study presents the effect of Al₂O₃ nanofluid (NF) on thermal performance of screen mesh heat pipe in cooling applications. Three cylindrical copper heat pipes of 200 mm length and 6.35 mm outer diameter containing two layers of screen mesh were fabricated and tested with distilled water and water based Al₂O₃ NF with mass concentrations of 5% and 10% as working fluids. To study the effect of NF on the heat pipes thermal performance, the heat input is increased and then decreased consecutively and the heat pipes surface temperatures are measured at steady state conditions. Results show that using 5 wt.% of Al₂O₃ NF improves the thermal performance of the heat pipe for increasing and decreasing heat fluxes compared with distilled water, while utilizing 10 wt.% of Al₂O₃ NF deteriorates the heat pipe is found to be between 6% and 24% for increasing and between 20% and 55% for decreasing heat fluxes, while the thermal resistance increased between 187% and 206% for increasing and between 155% and 175% for decreasing steps in heat pipe with 10 wt.% of Al₂O₃ NF.

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1. Introduction

Heat pipe, as a two-phase heat transfer device, has been used for cooling application of high power electronic devises. The reason which makes it as a popular heat transfer device is its flexibility and high effective thermal performance in comparison with common thermal conductors such as metal rods and fins. The thermal performance of a heat pipe is influenced by many parameters such as wick type, porosity and permeability, working fluid, filling ratio and operation conditions such as orientation and heat input. During recent years, nanofluids (NFs) have been suggested as working fluids to enhance heat pipes thermal performance. Various types of NFs with different concentrations, particle sizes and shapes have been used and interesting results on thermal performance enhancement are achieved [1–9]. Liu and Zhu [10] studied effects of aqueous CuO NFs on thermal performance of a horizontal mesh heat pipe experimentally. They investigated the effects of nanoparticles mass concentration and operating pressure on thermal performance of the heat pipe. They found that the average evaporator wall temperatures of the heat pipe using NFs decreased compared with those of the heat pipe using deionized water which resulted in 60% smaller thermal resistance of the heat pipe at 1 wt.% CuO NF. Wang et al. [11] investigated experimentally thermal performance of a cylindrical miniature grooved heat pipe using aqueous CuO NF. It was found that the evaporation heat transfer coefficient and maximum heat flux were increased by one time and 35%, respectively when NF was used as a working fluid instead of water in the heat pipe. Hung et al. [12] performed experiments to investigate the effect of Al₂O₃/water nanofluid on heat pipe thermal performance. They studied the effects of nanofluids concentrations, tilt angle, heat pipe length and filling ratio on overall thermal conductivity of the heat pipe. They found that in all cases the optimal thermal performance for NF is much better than that of heat pipes with distilled water. Putra et al. [13] investigated experimentally the thermal performance of screen mesh wick heat pipe with various NF. The experiments were carried out to determine the influence of concentrations at different types of nanofluids. Al₂O₃/water, Al₂O₃/ethylene glycol, TiO₂/water, TiO₂/ethylene glycol and ZnO/ethylene glycol with different concentrations were charged in the screen mesh wick heat pipe. They found that the heat pipe with NF has higher heat transfer coefficient than with the base liquid. Moreover, their results showed that a thin nano porous layer coated the surfaces of the wick after using NF caused this enhancement due to promote good capillary structure. Some experimental studies on heat pipe performance with NFs are reviewed in Table 1.

Lips et al. [22] tested a flat grooved heat pipe to study the effect of nucleate boiling on the heat transfer performance of the heat

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Nomenclature

Α	area, m	Subscrip	scripts	
h	heat transfer coefficient, W/m ² K	е	evaporator	
Κ	thermal conductivity, W/m K	С	condenser	
L	length, m	eff	effective	
Q	heat input, W	vap	vapor	
R	thermal resistance, K/W			
Т	temperature, K			

pipe. The heat pipe with $70 \times 90 \text{ mm}^2$ was made of 88 longitudinal rectangular micro-grooves and methanol was used as a working fluid. During the experiments the heat input were increased and decreased frequently in order to investigate different operation conditions of flat grooved heat pipe. Their results showed that increasing the heat input facilitated nucleate boiling at the evaporator with decreased wall temperature of heat pipe. They concluded that the thermal performance of the flat heat pipe was improved at the presence of nucleate boiling in the grooves. Since the heat dissipated by circuit boards in electronic components increase and decrease frequently during their operations, it is necessary to study the heat pipe performance and limitations in different operation conditions. This is an important subject which is missing in the literature and this study contributes for better understanding of NFs influence on thermal performance of heat pipes in electronic devices where the power density changes alternatively during their operations. In this study, effects of NFs on thermal performance of the heat pipe during increasing and decreasing heat loads are studied. The heat pipe with Al₂O₃/water NF at two different concentrations of 5 and 10 wt.% were tested and the results were compared with those of heat pipe with distilled water.

2. Experimental apparatus and procedure

2.1. Working fluid

The water based Al_2O_3 NF with Silane as the surface modifier, manufactured by the two-step method, is produced by ItN Nanovation AG (Germany) where the NF's pH was adjusted to 9.1. Transmission electron microscopy (TEM) analysis of the nanoparticles size and morphology were performed and presented in Fig. 1. For determination of hydrodynamic, or dispersed, size of Al_2O_3 particles, dynamic light scattering (DLS) analysis was performed, and the result is shown in Fig. 2. Al_2O_3 particles were observed to have polygonic morphologies with particle size in the range of 100 nm–200 nm, as displayed in Fig. 1. DLS analysis shows dispersed particle size in the range of 100–400 nm, with the average hydrodynamic size of 235 nm. This shows that

NO AL	X
	ſ
200 nm	

Fig. 1. Tem images of alumina nanoparticles.

particles are slightly aggregated in the NF, which is related to the method used for the fabrication of Al₂O₃ particles.

TPS-analyser (HotDisk model 2500) which employs Transient Plane Source (TPS) method is used for measuring the thermal conductivity of NFs and the dynamic viscosity is measured with a rotating coaxial cylinder viscometer (Brookfield model DV-II+Pro with UL adapter). Figs. 3 and 4 show the thermal conductivity and viscosity of Al₂O₃ NF at different concentrations and temperatures. The results exhibit that the thermal conductivity and viscosity of the NF are strongly dependent on the concentration of nanoparticles as well as the temperature. It is observed that the thermal conductivity of the NF increased with both concentration and temperature increments while the viscosity of the NF increased significantly with the concentration increase but decreased with the temperature increase. The important finding from these results is that the increment in viscosity of the NF compared with the base fluid is more than two times higher than the thermal conductivity increment of the NF.

Nanofluid in heat pipe studied in literature.

Author	Heat pipe type	Nanofluid (size & concentration)	Effort
Autiloi	Heat pipe type	Nationulu (size & concentration)	Effect
Asirvathamet al. [14]	Screenmesh	Water based silver (58.35 nm & 0.009 vol%)	+
Kole and Day [15]	Screenmesh	Water based copper (122 nm to 164 nm & 0.5 wt.%)	+
Do et al. [16]	Screenmesh	Water based alomina (30 nm &2.4 wt.%)	+
Kang et al. [17]	Sintered	Water based silver (10 nm & 0.01 wt.%)	+
Liu et al. [18]	Grooved	Water based copper oxide (50 nm & 1.0 wt.%)	+
Kang et al. [19]	Grooved	Water based silver Ag-water (35 nm, 0.01 wt.%)	+
Ji et al. [20]	Oscillating	Water based alomina (80 nm to 20 µm & 0.5 wt.%)	+
Yang and Liu [21]	Thermosyphon	Water based copper oxide (50 nm & 1.5 wt.%)	+



Fig. 2. Hydrodynamic size distribution of alumina NFs measured by DLS.



Fig. 3. Thermal conductivity of Al₂O₃-water NFs at different concentrations.

2.2. Experimental apparatus

The experimental test facility consists of a cooling system with constant temperature bath and flow meter, a power supplier, a data acquisition system and the main test section, as shown in Fig. 5. Details of experimental equipments are listed in Table 2. The heat pipe is made of a copper tube with length of 20 cm and the wall thickness of 0.71 mm. Each heat pipe has 2 layers of 150 mesh screen distributed on the inner tube. Aperture size and wire diameter of screen mesh are 0.106 mm and 0.063 mm, respectively.

For the optimum performance and reliability in terms of charge amount and pressure inside the pipes, all heat pipes were built, evacuated and filled at Thermacore Co. which is one of the heat pipe manufacturers in Europe. The evaporator, adiabatic and condenser sections of the heat pipe were 50 mm, 100 mm and 50 mm long, respectively. At the evaporator section, an electrical cartridge heater provides uniform heat flux to the copper heating blocks attached to the heat pipe. The condenser section was cooled



Fig. 4. Viscosity of Al₂O₃-water NFs at different concentrations.

by circulating water in a constant-temperature cooling bath at the temperature and flow rate of 288 K and 51 kg/h, respectively for keeping steady cooling conditions in the condenser section.

The temperatures of the heat pipe surface were measured using five K-type thermocouples by mounting two thermocouples at the surface of the evaporator, one at the surface of the adiabatic section and the rest at the surface of the condenser section. During the tests the input power increased and then decreased monotonically and the steady state was attained approximately after 20 min.

3. Data reduction

The water based Al_2O_3 nanofluid with mass concentrations of 5% and 10% were used to investigate the evaporator heat transfer coefficient and thermal resistance of the heat pipe. The temperature drop between evaporator and condenser and consequently the thermal resistance of a heat pipe is of particular interest to evaluate its thermal performance. The overall thermal resistance is comprised of a series-parallel combination of different resistances which causes a temperature drop between the two ends of the heat pipe [23]. The overall thermal resistance of the heat pipe is calculated from:

$$R = \frac{T_e - T_c}{Q} \tag{1}$$

where Q, T_e and T_c are heat input, evaporator and condenser wall temperatures, respectively. Also, the evaporator heat transfer coefficient is calculated by:

$$h_e = \frac{Q_e}{A_e \Delta T_e} \tag{2}$$

where the evaporator temperature difference is defined as:

$$\Delta T_e = T_e - T_{vap} \tag{3}$$

In Eq. (2) Q_e is the heat input to the evaporator section. Since the axial heat flow through the heat pipe wall at the evaporator is very low [23] it can be assumed that all the heat input is transferred to the working fluid in the evaporator. Hence, the heat load, Q, is used as the heat input to the evaporator. Moreover, T_{vap} is saturated steam temperature which can be measured from the surface of the adiabatic section [11]. This assumption is due to the axial temperature variation of the liquid and vapor regions in operating heat



Fig. 5. Diagram of the experimental set-up.

 Table 2

 Details of experiment setup.

 Pump
 Gear pump (MCP-Z, Ismatec, Switzerland)

 Flow-meter
 Coriolis flow meter (CMFS015, Micromotion, Netherlands)

 Data acquisition
 Agilent 34970A (Malaysia)

 system
 DC powersupplier (PSI 9080-100, Elektro-Automatik GmbH, Germany)

pipes. Peterson [23] motivated this simplification based on steadily decrease in the vapor temperature through the evaporator region and on into the adiabatic section due to slight decrease in the vapor pressure and smaller temperature gradient in the vapor region than in the liquid region along the pipe as well as the fact that the vapor temperature is lower than the external wall temperature in the evaporator while it is higher than the external wall temperature in the condenser make it possible to employ this assumption with acceptable accuracy. Although, the inner wall surface temperature of the evaporator should be used in the calculation of the evaporator heat transfer coefficients. Since the radial thermal resistance of the heat pipe wall is very low ($\sim 10^{-3} \circ C/W$) the measured outer surface temperature can be used with an acceptable accuracy.

Finally, the heat pipe effective thermal conductivity is defined as [24]:

$$K_{eff} = \frac{L_{eff}}{A_c R} \tag{4}$$

where A_c is the cross sectional area of the heat pipe and L_{eff} is effective transport length calculated by [24]:

$$L_{eff} = 0.5L_{\text{evaporator}} + L_{\text{adiabatic}} + 0.5L_{\text{condenser}}$$
(5)

The maximum calibration error of the thermocouples was ± 0.2 K. Moreover, based on the method proposed by Kline [25], the maximum uncertainties of the heat flux and thermal resistance were found to be less than 5.5% and 7%, respectively.

4. Result and discussion

To investigate the effect of utilizing NFs on thermal performance of a heat pipe, three different heat pipes containing distilled water as a reference and two water based Al_2O_3 NFs at mass concentrations of 5% and 10% were tested. The heat input was increased and then decreased consecutively and the heat pipes surface temperatures were measured and recorded at steady state conditions. Fig. 6 shows the evaporator wall temperature at different heat fluxes and for successive increasing and decreasing heat fluxes. As can be seen, the evaporator wall temperature decreased between 3% and 7% for increasing and between 6.5% and 9% for decreasing steps in the heat pipe with 5 wt.% Al_2O_3 NF compared with water. But, the evaporator wall temperature increased



Fig. 6. The evaporator wall temperature at different increasing (a) and decreasing (b) heat fluxes.



Fig. 7. The evaporator wall temperature at increasing and decreasing heat fluxes for (a) DW, (b) 5 wt.% Al₂O₃ NF and (c) 10 wt.% Al₂O₃ NF.

between 25% and 30% for increasing and between 25% and 30% for decreasing steps in the heat pipe with 10 wt.% Al₂O₃ NFs. Also, Fig. 7 reveals the comparison between the evaporator wall temperatures for increasing and decreasing steps at each concentration. It is observed from this figure that for the heat pipe with water, the evaporator wall temperature is higher for decreasing step in comparison with increasing one. This evaporator wall temperature variation for increasing and decreasing heat fluxes may be interpreted based on the heat transfer mechanism [26] at the evaporator and the heat exchange time at condenser. It is apparent that the evaporation behavior at each heat flux is influenced by the heat flux at previous step. At higher heat fluxes the probability of bubble generation increases, so, bubble size, growth and movement rates have influence on blocking the liquid return from the condenser to the evaporator. For decreasing heat flux, due to higher heat flux at previous steps, it is possible that a larger number of bubbles, generated on the evaporator surface at higher heat fluxes, coalesce into bigger bubbles with lower thermal conductivity and consequently leads to the decrease of capillary pumping ability and heat transfer performance [27,28,13]. In addition, the heat exchange time at condenser has remarkable influence on heat pipe thermal performance. For decreasing heat flux, due to higher working fluid temperature at previous heat flux, the heat dissipation efficiency at the condenser section decreases and the liquid returns back to the evaporator at higher temperature in comparison with the increasing flux. Hence, it is expected that the evaporator wall temperature is higher for decreasing heat flux compared with increasing heat flux.

But, as shown for the heat pipe with 5 wt.% of Al₂O₃ NF, the evaporator wall temperatures for increasing and decreasing steps are almost the same. The reasons of this thermal behavior of the heat pipe with nanofluid can be explained by evaluation of heat transfer mechanism in evaporation with NF. In a system with two phase heat transfer, the heat transfer performance is affected by different parameters. The working fluid properties, such as the thermal conductivity and surface tension; the heat transfer surface properties, such as the material, wettability, orientation, and surface roughness and finally the system properties, such as system pressure and the fluid surface interaction have significant influence on two phase heat transfer mechanism [29]. Many experimental studies are performed to identify NF effect on two phase heat transfer and they indicate that NFs can enhance or deteriorate heat transfer performance [30–33]. But, it is observed in nearly every study that a complex nano/micro porous layer of the nanoparticles forms on the surface of heated surface [32–37]. The presence of this porous layer and its characteristics has an important impact on evaporation/boiling heat transfer through changes in heated surface properties. It is reported that the presence of this layer alters the surface wettability and roughness and number of nucleation site present on the surface [29-37]. The reduction in evaporator wall temperature for decreasing heat flux at heat pipe with 5 wt.% of NF compared with other cases may be attributed to the effect of NFs on vapor bubble formation by bombarding the vapor bubbles by nanoparticles during their formation [38], the increase of active nucleation site density and bubble departure frequency [28,39-41]. In fact, the problem of blocking the liquid to be supplied to the entire evaporator surface at higher heat fluxes may be eliminated by bombarding the vapor bubbles during their formation with nanoparticles. According to above description, it is expected that the same trend occurs in the heat pipe with 10 wt.% of Al₂O₃ nanofluid, but, the experimental results at this concentration are not in agreement with those of the heat pipe with 5 wt.% of Al₂O₃ NF which shows the effect of NF concentration on working fluid properties and porous layer characteristics.

The evaporator heat transfer coefficient ratios between NF and water for increasing and decreasing steps are shown in Fig. 8. As can be seen, using 5 wt.% of Al_2O_3 NF increased the heat transfer coefficient of the heat pipe for both increasing and decreasing steps. In contrast, the evaporator heat transfer ratios for the heat pipe with 10 wt.% Al_2O_3 NF for increasing and decreasing steps drop below unity which shows that at this concentration utilizing Al_2O_3 NF is not beneficial for the heat pipe performance. The reasons of heat pipe performance deterioration with 10 wt.% of



Fig. 8. The evaporator heat transfer coefficient ratios between nanofluid and water.



Fig. 9. SEM images of the evaporator wick surface (a) before testing with NF and after testing with (b) 5 wt.% Al₂O₃ NF and (c) 10 wt.% Al₂O₃ NF.

 Al_2O_3 NF may be due to the evaporator wick surface structure and also two times higher viscosity increase at this concentration compared with Al_2O_3 NF at mass concentration of 5%. At higher nanoparticle concentration, partial detachment of the nanoparticle layer is imminent and unavoidable because of not very firm adhesion of the nanoparticles to the wick surface [42]. So, a significant reduction of evaporator heat transfer coefficient is detected after detachment.

To explain the reasons of the apparent discrepancy between thermal performance of the heat pipes with 5 wt.% and 10 wt.% of Al₂O₃ nanofluids, thermal properties and rheological behavior of the nanofluids and the nature of the wick after the micro/nano porous layer formation was studied. Fig. 9 shows the SEM images of the wick surface for the heat pipes with 5 wt.% and 10 wt.% Al₂O₃ NFs. As can be seen, a normal spread of nanoparticles with larger number of pores in the porous layer for the case with 5 wt.% of NF results in increasing the capillary force and also wettability which makes the rewetting process much easier and consequently helps the working fluid to return back to the evaporator at higher rate and increase the heat transfer area on heated surface in the evaporator.

Unlike heat pipe with 5 wt.% Al₂O₃ nanofluid, for the heat pipe with 10 wt.% Al₂O₃ NF SEM images reveal that the agglomeration and aggregation of the nanoparticles form an unusual layer on the surface of the wick. A layer of aggregated and agglomerated particles affects the surface roughness, surface tension, and bubble departure frequency negatively and decrease the active nucleation site density. Fig. 10 shows the total thermal resistance of the heat

pipes for increasing and decreasing steps. Results indicate that the thermal resistance of the heat pipes was noticeably affected by utilizing Al₂O₃ nanofluid. The total thermal resistance of the heat pipe decreased between 24% and 6% for increasing and between 20% and 55% for decreasing steps when water is replaced with 5 wt.% Al₂O₃ NFs. In contrast, the total thermal resistance of the heat pipe increased between 187% and 206% for increasing and between 155% and 175% for decreasing steps for the heat pipe with 10 wt.% Al₂O₃ NFs. The comparison between the thermal resistances of the heat pipes for increasing and decreasing heat fluxes at each concentration is shown in Fig. 11.

As discussed earlier, when water is replaced with NF, an inconsistence thermal behavior is observed due to the changes in fluid and surface properties. For the heat pipe with 5% Al₂O₃ NF a reduction up to 10% in thermal resistance for decreasing step compared with increasing one is observed while for the heat pipe with 10% Al₂O₃ NF the thermal resistance increased for decreasing step with the same trend as the case with water. It shows the importance of the heat transfer mechanism role on evaluation of heat pipes thermal performance at the presence of NF as a working fluid. The higher increment in viscosity of the 10 wt.% Al₂O₃ NF in comparison with its thermal conductivity and also compared with the viscosity increment of 5 wt.% Al₂O₃ NF causes a reduction in the capillary pumping ability of the wick and is one of the reasons for deterioration of the heat pipe performance with 10 wt.% Al₂O₃ NF.

It is revealed by the SEM images that the surface of the wick for the heat pipe with 10% of Al_2O_3 nanofluid is covered by an



Fig. 10. The thermal resistance of the heat pipes for increasing (a) and decreasing (b) steps.



Fig. 11. The comparison between the thermal resistances of the heat pipes for (a) DW, (b) 5 wt.% Al₂O₃ NF and (c) 10 wt.% Al₂O₃ NF.



Fig. 12. Effective thermal conductivity of the heat pipes for increasing (a) and decreasing (b) power steps.

aggregated and agglomerated particles blanket. Local surface deficiencies produced during the nanoparticle layer detachment at this concentration had negative effect on two phase heat transfer [41]. In addition, the presence of surfactants and the surface contamination may obstruct working fluid movement and liquid stirring which indicates that NFs are not beneficial for the heat pipe performance at all concentrations.

Finally, the effective thermal conductivity (based on Eq. (4)) of the heat pipes are studied to give a sensible view about the advantage and/or disadvantage of utilizing Al_2O_3 NFs at different concentrations as a working fluid in the heat pipes. As shown in Fig. 12, using 5 wt.% of Al_2O_3 NFs results in a significant increment for both increasing and decreasing heat fluxes in comparison with water. The increment in effective thermal conductivity for the heat pipe with 5 wt.% Al_2O_3 NF is found to be 30% at lower heat fluxes (7.5 W and 15 W) and decreased to 7% at 35 W for increasing heat fluxes. For the same heat pipe and for decreasing heat fluxes the increment in effective thermal conductivity was 25% at 35 W and increased up to 130% at 7.5 W. For the heat pipe with 10 wt.% Al_2O_3 NF the effective thermal conductivity decreased 67% and 63% for increasing and decreasing heat fluxes, respectively.

Moreover, it is observed that for the heat pipe with 5 wt.% of Al₂O₃ NF and comparing with water the effective thermal conductivity difference for decreasing step is higher compared with increasing step which show the advantage of employing heat pipe with NF in electronic cooling devices where the power density changes alternatively during operations. Also, compared with metal fins and rods with about one or two order of magnitudes

lower thermal conductivity it is very beneficial to employ heat pipe with proper concentrations of NFs in cooling and thermal management applications.

5. Conclusion

An experimental study was performed to investigate the thermal performance of screen mesh heat pipes using distilled water and water based Al_2O_3 NFs with mass concentrations of 5% and 10% as working fluids, focusing on heat pipes thermal behavior for increasing and decreasing heat fluxes. The following conclusions are drawn from this study:

- The thermal performance of the heat pipe increases utilizing 5 wt.% Al₂O₃ NF while decreases with 10 wt.% Al₂O₃ NF compared with distilled water.
- Thermal performance of the heat pipe for increasing and decreasing heat fluxes is largely influenced by the heat flux at previous step. The thermal resistance of the heat pipe increases with distilled water and 10 wt.% Al₂O₃ NF for decreasing heat flux compared with increasing heat flux but decreases for decreasing heat flux with 5 wt.% of Al₂O₃ NF.
- The results revealed that the effective thermal conductivity of the heat pipe increases up to 30% and 130% at different heat inputs for increasing and decreasing heat fluxes, respectively, for the heat pipe with 5 wt.% Al₂O₃ NF while it decreases up to 67% and 63% for the case with 10 wt.% Al₂O₃ NF.

- The main probable reasons for the enhancement in the thermal performance of the heat pipe with 5 wt.% Al₂O₃ NF are bombarding the vapor bubbles during bubble formation by nanoparticles, increasing the wettability and capillary force and increase of heat transfer area in the evaporator by forming a thin porous layer of Al₂O₃ particles on the surface of the wick.
- In contrast, the thermal performance of the heat pipe with 10 wt.% Al₂O₃ NF decreases due to forming an aggregated and agglomerated particles blanket with weak adhesion of the particles to the heated surface as well as much higher viscosity increment of the 10 wt.% Al₂O₃ NF compared with 5 wt.% Al₂O₃ NF.

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